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# Search for new physics in events with same-sign dileptons and b-tagged jets in pp collisions at $\sqrt{s} = 7$ TeV

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## The CMS collaboration

**ABSTRACT:** A search for new physics is performed using isolated same-sign dileptons with at least two b-quark jets in the final state. Results are based on a  $4.98 \text{ fb}^{-1}$  sample of proton-proton collisions at a centre-of-mass energy of 7 TeV collected by the CMS detector. No excess above the standard model background is observed. Upper limits at 95% confidence level are set on the number of events from non-standard-model sources. These limits are used to set constraints on a number of new physics models. Information on acceptance and efficiencies are also provided so that the results can be used to confront additional models in an approximate way.

**KEYWORDS:** Hadron-Hadron Scattering

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**Contents**

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>Introduction</b>  | <b>1</b>  |
| <b>2</b> | <b>CMS detector</b>  | <b>2</b>  |
| <b>3</b> | <b>Event selection</b>   | <b>3</b>  |
| <b>4</b> | <b>Background estimation</b>   | <b>4</b>  |
| <b>5</b> | <b>Search results</b>  | <b>5</b>  |
| <b>6</b> | <b>Efficiencies and associated uncertainties</b>   | <b>6</b>  |
| <b>7</b> | <b>Information for model testing</b>   | <b>8</b>  |
| <b>8</b> | <b>Models of new physics</b>   | <b>10</b> |
| 8.1      | Models of $pp \rightarrow t\bar{t}$  | 10        |
| 8.2      | Models with four top quarks and two LSPs from gluino pair production and decay via real or virtual top squarks | 11        |
| 8.3      | Models with multiple top quarks and W-bosons from decays of bottom squarks                                     | 12        |
| <b>9</b> | <b>Conclusions</b>   | <b>15</b> |
|          | <b>The CMS collaboration</b>   | <b>19</b> |

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**1 Introduction**

We present a search for anomalous production of events with two like-sign isolated leptons ( $e$  or  $\mu$ ) and b-quark jets. In proton-proton collisions at the Large Hadron Collider (LHC) such events from standard model (SM) processes are rare; their anomalous production would be an indication of new physics. While in general the hadronic jets in new physics processes can originate from gluons or light flavour quarks, there is a range of well-established models predicting the presence of two to four b-quark jets in such events. These appear in signatures of supersymmetry (SUSY) where bottom- and top-quark superpartners are lighter than other squarks [1–5], enhancing the fraction of strongly produced SUSY particles resulting in top and bottom quarks in the final states. Here, the signatures with two like-sign leptons, b-quark jets and missing transverse energy correspond to strongly produced SUSY processes with multiple W bosons appearing in the decay chains, either from top quarks or charginos. In addition to SUSY processes, the existence of a  $Z'$ -boson with flavour-violating  $u$ - $t$  quark coupling [6, 7] would lead to like-sign top pair production,  $uu \rightarrow t\bar{t}$  via  $Z'$  exchange, at the LHC. Such a boson has been proposed to explain the

top-quark pair forward-backward production asymmetry observed at the Tevatron [8–10]. A similar topology is expected in models of maximal flavour violation (MxFV) [11–13].

Experimentally, events with two isolated like-sign leptons and jets, selected without b-quark jet identification (b-tagging), are dominated by  $t\bar{t}$  production [14, 15], with one lepton from W decay and the other lepton from the semileptonic decay of a b quark. In a same-sign dilepton selection the requirement of at least two b-tagged jets strongly suppresses the  $t\bar{t}$  background, since the two b quarks in  $t\bar{t}$  are very unlikely to produce three distinct objects, i.e., two b-tagged jets and one isolated high transverse momentum ( $p_T$ ) lepton.

The search is performed on a data set corresponding to an integrated luminosity of  $4.98\text{ fb}^{-1}$  collected by the Compact Muon Solenoid (CMS) [16] detector in proton-proton collisions at  $\sqrt{s} = 7\text{ TeV}$  delivered by the LHC in 2011. This work relies heavily on the event selections and background estimation methods of the previous CMS inclusive same-sign dilepton searches not requiring b-tagged jets in the final state [14, 15, 17]. Compared with the most recent analysis [15], a more stringent isolation requirement is applied to further suppress backgrounds with misidentified leptons. In addition, the lepton transverse momenta are required to be above 20 GeV, as is typical for leptons from W decays that are expected to be present in the signals of interest. The rest of the data analysis is unchanged.

The search described in this paper is based on the comparison of the number of observed events with expectations from SM processes. A loose baseline selection is defined first. Selections with tighter requirements on the missing transverse energy ( $E_T^{\text{miss}}$ ) and on the scalar sum of jet  $p_T$  ( $H_T$ ) are then used to provide better sensitivity to potential signal models.

Since we find no excess of events over the SM background prediction, we provide a recipe to set limits on any model with same-sign dileptons, missing transverse energy, and b-quark jets. The recipe relies on efficiency functions to be used to emulate the selection efficiencies for leptons, jets, and  $E_T^{\text{miss}}$ . These functions can then be applied to a signal simulated at the matrix-element level.

As a reference, we also provide constraints on several models representative of this topology. The signal topologies with two b-quark jets in the final states are: like-sign top quark production in the  $Z'$  model [6] and in the MxFV model [13]; production of two bottom squarks each decaying as  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ . In the latter case  $\tilde{\chi}_1^- \rightarrow W^- \tilde{\chi}_1^0$ , where  $\tilde{\chi}_1^0$  is the lightest supersymmetric particle (LSP). The topologies with more than two b-quark jets are:  $\tilde{g}\tilde{g}$  or  $\tilde{g}\tilde{b}$ , with  $\tilde{g} \rightarrow \tilde{b}_1\bar{b}$  and  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ , as above;  $\tilde{g}\tilde{g}$  with both gluinos giving a  $t\bar{t}\tilde{\chi}_1^0$  final state with an intermediate virtual or on-shell top squark.

## 2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. CMS uses a right-handed coordinate system, with the origin defined to be the nominal interaction point, the  $x$  axis pointing to the center of the LHC ring, the  $y$  axis pointing up (perpendicular to the LHC plane), and the  $z$  axis pointing in the anticlockwise beam direction. The polar angle  $\theta$  is measured from the positive  $z$  axis

and the azimuthal angle  $\phi$  is measured in the  $x$ - $y$  (transverse) plane. The pseudorapidity  $\eta$  is defined as  $\eta = -\ln(\tan\theta/2)$ . Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Full coverage is provided by the tracker, calorimeters, and the muon detectors within  $|\eta| < 2.4$ . In addition to the barrel and endcap detectors up to  $|\eta| = 3$ , CMS has extensive forward calorimetry reaching  $|\eta| \lesssim 5$ . A more detailed description can be found in ref. [16].

### 3 Event selection

Dilepton events used in the analysis are selected by the CMS trigger system if there are at least two leptons (electrons or muons) reconstructed online. The trigger selects pairs of leptons above adjustable thresholds on  $p_T$  for muons and  $E_T$  for electrons, where  $E_T$  is defined as the energy measured in the ECAL projected on the transverse plane. For dielectrons and electron-muon events the thresholds are 17 GeV on the first lepton and 8 GeV on the second lepton. For dimuon events the requirements on  $p_T$  for the higher (lower) threshold changed as the luminosity increased during data taking from 7 (7) GeV, to 13 (8) GeV, and finally reaching 17 (8) GeV.

Electron candidates are reconstructed using measurements provided by the tracker and the ECAL [18]. Muon candidates are reconstructed using a combination of measurements in the silicon tracker and the muon detectors [19]. Two leptons of the same sign,  $p_T > 20$  GeV, and  $|\eta| < 2.4$ , are required in each event. Electron candidates in the transition region between the barrel and endcap calorimeters ( $1.442 < |\eta| < 1.566$ ) are not considered in the analysis. The two leptons must be consistent with originating from the same collision vertex. Additional identification requirements are applied to suppress backgrounds in the same way as in the inclusive same-sign dilepton analysis [15]. The isolation requirement is applied on a scalar sum of the track  $p_T$  and calorimeter  $E_T$  measurements, computed in a cone of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  relative to the lepton candidate momentum. This sum must be less than  $0.1p_T$  of the candidate itself. The two lepton candidates are required to have an invariant mass  $m(\ell\ell)$  above 8 GeV to suppress backgrounds from b-hadron decays. Events with any third lepton with  $p_T > 10$  GeV and isolation sum below  $0.2p_T$  are rejected if this lepton forms an opposite-sign same-flavour pair having  $76 \text{ GeV} < m(\ell\ell) < 106 \text{ GeV}$  with either of the selected leptons. This requirement suppresses the diboson WZ background.

Jets and missing transverse energy are reconstructed by the particle-flow algorithm [20–22]. Jets are clustered using the anti- $k_T$  algorithm [23] with a distance parameter  $R = 0.5$ . Jet energies are corrected by subtracting the average contribution from particles from other proton-proton collisions in the same beam crossing (pileup) and by correcting the jet momentum to better reflect the true total momentum of the particles in the jet [21]. At least two jets with  $p_T > 40$  GeV and  $|\eta| < 2.5$  are required in each event. The baseline selection places no requirement on the magnitude of the  $E_T^{\text{miss}}$  vector, computed as the negative of the vector sum of all particle-flow candidate momenta in the transverse plane.

At least two of the selected jets with  $|\eta| < 2.4$  are required to be b-tagged using the simple secondary vertex tagger at a medium operating point (SSVHEM) [24, 25]. This b-tagging algorithm requires the reconstruction of a secondary vertex, with at least two associated tracks, displaced from the primary collision vertex. The algorithm has an efficiency between 40–65% for b-quark jets with  $p_T > 40$  GeV and a misidentification rate for light-quark jets of a few percent, increasing with the transverse momentum.

Events passing the selections described above constitute the baseline same-sign dilepton sample. There are 10 such events observed in data: 3 ee, 2  $\mu\mu$ , and 5  $e\mu$ .

## 4 Background estimation

There are three distinct background contributions to this search: events with one or two “fake” leptons, rare SM processes that yield events with two isolated same-sign leptons, and events with opposite-sign lepton pairs with a lepton charge misreconstructed (“charge-flips”). Here we define the term “fake lepton” to refer to a lepton from heavy flavour decay, an electron from unidentified photon conversion, a muon from meson decays in flight, or a hadron misidentified as a lepton. The backgrounds, which are further discussed below, are estimated using the same techniques as in the inclusive analysis [14, 15]: the fake and charge-flip backgrounds are estimated from control data samples, while the rare SM backgrounds are determined from simulation.

The background from fakes is estimated from events where one or both leptons fail the tight isolation and identification selection, but still pass a looser selection. Counts of events in this control sample are weighted by the expected ratio (“tight-to-loose”, or TL ratio) of the rate of fake leptons passing the selection to that of those failing it. This TL ratio is measured as a function of lepton type,  $p_T$ , and  $\eta$ , in a data sample of events with a single lepton candidate and a well separated jet (“away-jet”). After vetoing Z candidates and suppressing leptons from W decays by requiring small  $E_T^{\text{miss}}$  and transverse mass, the leptons in this sample are predominantly fakes. The systematic effects on the method to estimate events with fake leptons arise from differences in kinematics and sample composition between the sample where the TL ratio is measured and the sample where it is applied. The systematic uncertainty on the method is taken to be 50%. This uncertainty is based on tests of the ability of this method to predict the same-sign dilepton background in simulated  $t\bar{t}$  events; it is also based on the observed variations of the TL ratio as a function of the  $p_T$  threshold of the away jet and the addition of a b-tag requirement on that jet.

The baseline sample is estimated to have  $1.5 \pm 1.1$ ,  $0.8 \pm 0.5$ , and  $2.4 \pm 1.4$  events with fake leptons in the ee,  $\mu\mu$ , and  $e\mu$  final states, respectively. These uncertainties include a statistical uncertainties based on the number of events passing the loose lepton selection, as well as the 50% systematic uncertainty.

As mentioned above, we estimate, from simulation, the contribution to the event count from rare SM processes yielding isolated high- $p_T$  same-sign dileptons and jets. Events are generated with the MADGRAPH [26] event generator and then passed on to PYTHIA [27] for parton shower and hadronization. The generated events are processed by the CMS event simulation and the same chain of reconstruction programs as is used for collision

data. As determined from simulation, we find that background events from  $t\bar{t}W$  and  $t\bar{t}Z$  production represent more than 90% of all the genuine same-sign dilepton backgrounds. Other processes considered include production of diboson (WZ, ZZ, same-sign WW) and triboson (combinations of W and Z) final states. Compared to the inclusive analysis [15], these backgrounds are strongly suppressed by the b-tagging requirement. Backgrounds like  $(W/Z)\gamma$  and  $t\bar{t}\gamma$  are considered as well to simulate events with a photon converting in the tracker material and misidentified as an electron. Their contribution is negligibly small. A conservative systematic uncertainty of 50% is assigned to the total number of background events from simulation, since these are rare SM processes which have yet to be observed. The production cross sections used to normalize the dominant  $t\bar{t}W$  and  $t\bar{t}Z$  contributions are 0.16 pb [28] and 0.14 pb [29, 30], respectively. In the baseline sample the simulated rare SM backgrounds are determined to contribute  $0.9 \pm 0.5$ ,  $1.1 \pm 0.6$ , and  $2.0 \pm 1.0$  events in the  $ee$ ,  $\mu\mu$ , and  $e\mu$  final states, respectively.

Events with opposite-sign lepton pairs where one of the leptons has an incorrectly measured charge (charge-flip) contribute to the same-sign dilepton sample. The charge-flip probability for muons is of order  $10^{-4}$ – $10^{-5}$  and can be neglected. In contrast, this probability for electrons from W or Z decay is estimated in simulation to be about  $10^{-3}$ . The number of same-sign events due to charge-flips is given by the number of opposite-sign events passing the same selections with a weight applied to each electron corresponding to its charge misidentification probability. We determine this probability in simulation as a function of electron  $p_T$  and  $\eta$ . The method is tested in data by using the  $Z \rightarrow e^+e^-$  sample and the probability mentioned above to predict the number of  $e^\pm e^\pm$  events with invariant mass consistent with the Z mass. This prediction is found to be in good agreement with the number of events of this type in data. A systematic uncertainty of 20% is estimated for this method based on variation in the average charge misidentification rate between typical lepton momenta in Z and  $t\bar{t}$  events. In the baseline sample the charge-flip contribution is estimated to be  $0.8 \pm 0.2$  and  $0.6 \pm 0.1$  events in the  $ee$  and  $e\mu$  final states, respectively.

## 5 Search results

After the basic selection described in section 3, we define several “signal regions” (SR) with increasing requirements on  $H_T$  and  $E_T^{\text{miss}}$  with respect to the baseline selection. These requirements improve the sensitivity to new physics models with high mass scales and/or high  $E_T^{\text{miss}}$  from, e.g., high  $p_T$  non interacting particles, such as LSPs in SUSY models. We also define a SR with minimal requirements on  $H_T$  and  $E_T^{\text{miss}}$  but allowing only for positive leptons. This region is designed to be sensitive to  $pp \rightarrow t\bar{t}$  production (in most models  $pp \rightarrow t\bar{t}$  is suppressed with respect to  $pp \rightarrow tt$  since at the parton level these processes originate from  $\bar{u}u$  and  $uu$  initial states, respectively). Additionally, we define a SR with moderate  $H_T$  and  $E_T^{\text{miss}}$  requirements and three or more b-tagged jets. This region can improve the sensitivity to models of new physics with several ( $\geq 3$ ) b quarks in the final state. However, for the models considered here (section 8) we find that inclusion of this region does not improve the sensitivity. This is because the increase in efficiency due to the looser  $H_T$  and  $E_T^{\text{miss}}$  requirements does not compensate for the efficiency loss associated

|                     | SR0            | SR1           | SR2           | SR3             | SR4           | SR5             | SR6             | SR7               | SR8             |
|---------------------|----------------|---------------|---------------|-----------------|---------------|-----------------|-----------------|-------------------|-----------------|
| No. of jets         | $\geq 2$       | $\geq 2$      | $\geq 2$      | $\geq 2$        | $\geq 2$      | $\geq 2$        | $\geq 2$        | $\geq 3$          | $\geq 2$        |
| No. of b-tags       | $\geq 2$       | $\geq 2$      | $\geq 2$      | $\geq 2$        | $\geq 2$      | $\geq 2$        | $\geq 2$        | $\geq 3$          | $\geq 2$        |
| Lepton charges      | $++/--$        | $++/--$       | $++$          | $++/--$         | $++/--$       | $++/--$         | $++/--$         | $++/--$           | $++/--$         |
| $E_T^{\text{miss}}$ | $> 0$ GeV      | $> 30$ GeV    | $> 30$ GeV    | $> 120$ GeV     | $> 50$ GeV    | $> 50$ GeV      | $> 120$ GeV     | $> 50$ GeV        | $> 0$ GeV       |
| $H_T$               | $> 80$ GeV     | $> 80$ GeV    | $> 80$ GeV    | $> 200$ GeV     | $> 200$ GeV   | $> 320$ GeV     | $> 320$ GeV     | $> 200$ GeV       | $> 320$ GeV     |
| Charge-flip BG      | $1.4 \pm 0.3$  | $1.1 \pm 0.2$ | $0.5 \pm 0.1$ | $0.05 \pm 0.01$ | $0.3 \pm 0.1$ | $0.12 \pm 0.03$ | $0.03 \pm 0.01$ | $0.008 \pm 0.004$ | $0.20 \pm 0.05$ |
| Fake BG             | $4.7 \pm 2.6$  | $3.4 \pm 2.0$ | $1.8 \pm 1.2$ | $0.3 \pm 0.5$   | $1.5 \pm 1.1$ | $0.8 \pm 0.8$   | $0.15 \pm 0.45$ | $0.15 \pm 0.45$   | $1.6 \pm 1.1$   |
| Rare SM BG          | $4.0 \pm 2.0$  | $3.4 \pm 1.7$ | $2.2 \pm 1.1$ | $0.6 \pm 0.3$   | $2.1 \pm 1.0$ | $1.1 \pm 0.5$   | $0.4 \pm 0.2$   | $0.12 \pm 0.06$   | $1.5 \pm 0.8$   |
| Total BG            | $10.2 \pm 3.3$ | $7.9 \pm 2.6$ | $4.5 \pm 1.7$ | $1.0 \pm 0.6$   | $3.9 \pm 1.5$ | $2.0 \pm 1.0$   | $0.6 \pm 0.5$   | $0.3 \pm 0.5$     | $3.3 \pm 1.4$   |
| Event yield         | 10             | 7             | 5             | 2               | 5             | 2               | 0               | 0                 | 3               |
| $N_{UL}$ (12% unc.) | 9.1            | 7.2           | 6.8           | 5.1             | 7.2           | 4.7             | 2.8             | 2.8               | 5.2             |
| $N_{UL}$ (20% unc.) | 9.5            | 7.6           | 7.2           | 5.3             | 7.5           | 4.8             | 2.8             | 2.8               | 5.4             |
| $N_{UL}$ (30% unc.) | 10.1           | 7.9           | 7.5           | 5.7             | 8.0           | 5.1             | 2.8             | 2.8               | 5.7             |

**Table 1.** A summary of the results of this search. For each signal region (SR), we show its most distinguishing kinematic requirements, the prediction for the three background (BG) components as well as the total, the event yield, and the observed 95% confidence level upper limit on the number of non-SM events ( $N_{UL}$ ) calculated under three different assumptions for the event efficiency uncertainty (see text for details). Note that the count of the number of jets on the first line of the table includes both tagged and untagged jets.

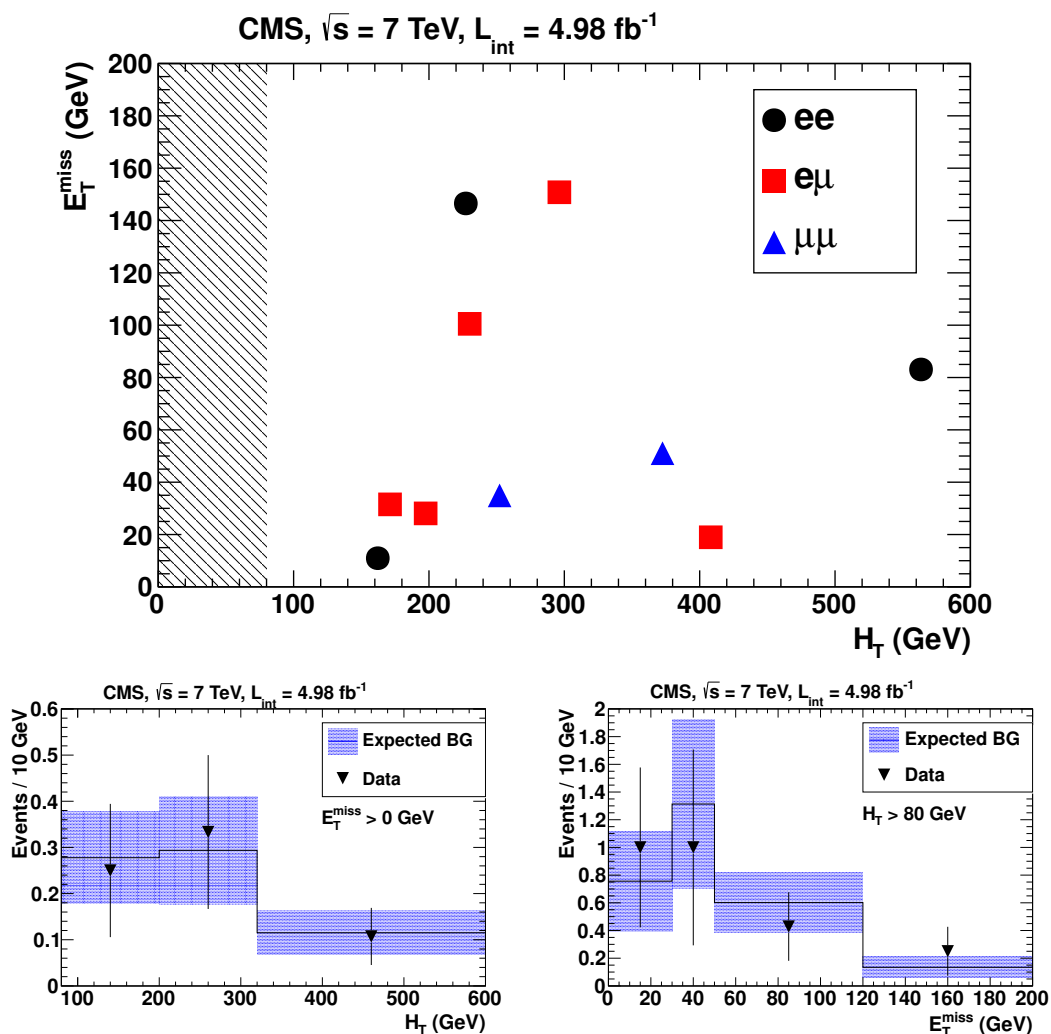
with the requirement of a third b-tag. Finally, we define a SR with a high  $H_T$  requirement and no  $E_T^{\text{miss}}$  requirement. This region is designed to enhance sensitivity to models with R-parity violating SUSY [31] with [32] or without [33, 34] leptonically decaying W bosons (the latter type of events have no intrinsic  $E_T^{\text{miss}}$  from undetected particles).

The definitions of the signal regions, the data event yields, and the expected backgrounds calculated for each SR, are summarized in table 1. Distributions of  $H_T$  and  $E_T^{\text{miss}}$  are also displayed in figure 1 for the baseline selection. Note that SR0 corresponds to the baseline event selection of section 3. The event yields are consistent with the background predictions. In table 1 we also show the 95% confidence level observed upper limit ( $N_{UL}$ ) on the number of non-SM events calculated using the  $CL_s$  method [35, 36] under three different assumptions for the signal efficiency uncertainty. This uncertainty is discussed in section 6.

## 6 Efficiencies and associated uncertainties

Events in this analysis are collected with dilepton triggers. The efficiency of the trigger is measured to be  $99 \pm 1\%$  ( $96 \pm 3\%$ ) per electron (muon) in the range  $|\eta| < 2.4$ . The efficiency of the lepton identification and isolation requirements, as determined using a sample of simulated events from a typical SUSY scenario (the LM6 point of ref. [37]), is displayed in figure 2. Studies of large data samples of  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  events indicate that the simulation reproduces the efficiencies of the identification requirements to better than 2% [18, 19]. The efficiency of the isolation requirement on leptons in Z events is also well reproduced by the simulation. However, this efficiency depends on the hadronic activity in the event, and is typically 10% lower in SUSY events with hadronic cascades than in Z events. To account for this variation, we take a 5% systematic uncertainty per lepton in the acceptance of signal events.



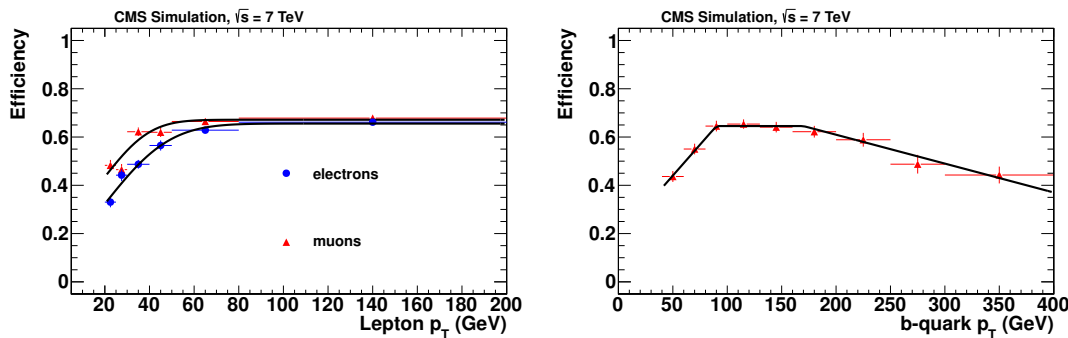


**Figure 1.** Top plot: distribution of  $E_T^{\text{miss}}$  vs.  $H_T$  for the 10 events in the baseline region (SR0). Note that the  $\geq 2$  jets requirement in SR0 implies  $H_T > 80$  GeV. Bottom left plot: projection of the scatter plot on the  $H_T$  axis. Bottom right plot: projection of the scatter plot on the  $E_T^{\text{miss}}$  axis. For the one-dimensional distributions, the number of events in each bin is scaled appropriately to reflect units of events per 10 GeV and is compared with the background (BG) predictions, with their uncertainties.

The b-tagging efficiency on simulated data is also shown in figure 2 for b quarks of  $|\eta| < 2.4$  and  $p_T > 40$  GeV. Study of a variety of control samples indicate that for collision data this efficiency needs to be reduced by a factor of 0.96, independent of  $p_T$ . This factor is applied to the simulation of possible new physics signals, e.g., all the models of section 8. The systematic uncertainty on the b-tagging efficiency is 4% (15%) for jets of  $p_T < 240$  GeV ( $p_T > 240$  GeV).

The energies of jets in this analysis are known to 7.5% (not all the corrections described in ref. [21] were applied, since they have little impact on the sensitivity of this search). The uncertainty on the jet energy scale has an effect on the efficiencies of the jet multiplicity,





**Figure 2.** Lepton selection efficiency as a function of  $p_T$  (left); b-jet tagging efficiency as a function of the b quark  $p_T$  (right).

$H_T$ , and  $E_T^{\text{miss}}$  requirements. The importance of these effects depends on the signal region and the model of new physics. For example, for the  $Z'$  model of section 8.1, the uncertainty on the acceptance of the SR2 requirements due to the imperfect knowledge of the jet energy scale is 8%. In general, models with high hadronic activity and high  $E_T^{\text{miss}}$  are less affected by this uncertainty.

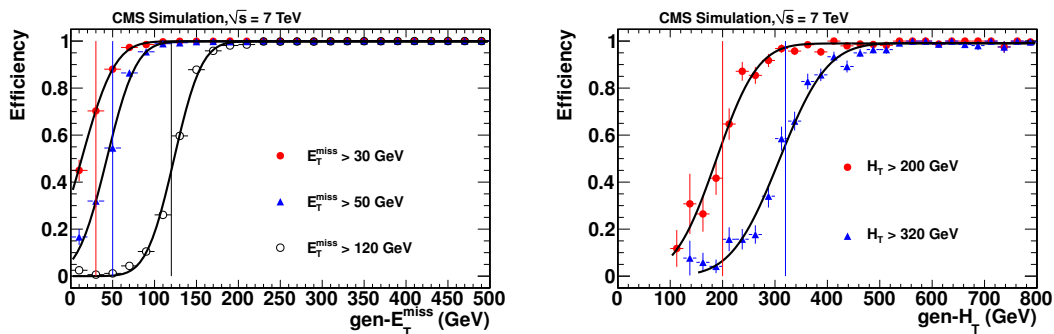
The total uncertainty on the acceptance is in the 12–30% range. Finally, there is a 2.2% uncertainty on the yield of events from any new physics model due to the uncertainty in the luminosity normalization [38].

## 7 Information for model testing

We have described a signature based search that finds no evidence for physics beyond the SM. In section 8 we will use our results to put bounds on the parameters of a number of models of new physics. Here we present additional information that can be used to confront other models of new physics in an approximate way by generator-level studies that compare the expected number of events with the upper limits from table 1.

The values of  $N_{UL}$  for the different signal regions are given in table 1 under different assumptions for the efficiency uncertainty. This is because, as discussed in section 6, this uncertainty depends on the model under test. The dependence of  $N_{UL}$  on the acceptance uncertainty is not very strong. Thus, for the purpose of generator-level model testing, the lack of precise knowledge of the uncertainty does not constitute a significant limitation.

The kinematic requirements on jets and leptons given in section 3 are the first ingredients of the acceptance calculation for a new model. Leptons at the hard-scatter level passing the kinematic selection can be counted, and this count can be corrected for the finite lepton efficiencies shown in figure 2, as well as the trigger efficiencies given in section 6. Similarly, the number of jets in the event can be approximated by counting the number of colored final-state partons of  $p_T > 40$  GeV and  $|\eta| < 2.5$  at the hard scatter level. A generator-level  $H_T$  variable,  $\text{gen-}H_T$ , can be calculated by summing the  $p_T$  of all the colored partons from the previous step; isolated photons and additional leptons of  $p_T > 40$  GeV and  $|\eta| < 2.5$  should also be included in the  $\text{gen-}H_T$  calculation. Similarly, a generator-level  $E_T^{\text{miss}}$  variable,  $\text{gen-}E_T^{\text{miss}}$ , can be defined from the vector sum of transverse momenta



**Figure 3.** Efficiency for an event to pass a given reconstructed  $E_T^{\text{miss}}$  or  $H_T$  threshold as a function of  $\text{gen-}E_T^{\text{miss}}$  or  $\text{gen-}H_T$ . The efficiencies are shown for the thresholds used in defining the signal regions.

| Parameter | $H_T$    |          | $E_T^{\text{miss}}$ |         |          |
|-----------|----------|----------|---------------------|---------|----------|
|           | >200 GeV | >320 GeV | >30 GeV             | >50 GeV | >120 GeV |
| $x_{1/2}$ | 188 GeV  | 308 GeV  | 13 GeV              | 43 GeV  | 123 GeV  |
| $\sigma$  | 88 GeV   | 102 GeV  | 44 GeV              | 39 GeV  | 37 GeV   |

**Table 2.** Parameters used in describing the turn-on curves for  $H_T$  and  $E_T^{\text{miss}}$  as a function of their generator-level values. See text for details.

of all non-interacting particles. Finally, the number of reconstructed b-quark jets can be obtained by counting the number of b quarks and applying the efficiency parametrization of figure 2, including the requirements  $p_T > 40$  GeV and  $|\eta| < 2.4$ . The efficiencies of the  $H_T$  and  $E_T^{\text{miss}}$  requirement after hadronization and detector simulation as a function of  $\text{gen-}H_T$  and  $\text{gen-}E_T^{\text{miss}}$  for a typical SUSY scenario are shown in figure 3.

The lepton efficiency curves of figure 2 are parametrized as

$$\epsilon = \epsilon_\infty \text{erf}\left(\frac{p_T - 20 \text{ GeV}}{\sigma}\right) + \epsilon_{20} \left(1 - \text{erf}\left(\frac{p_T - 20 \text{ GeV}}{\sigma}\right)\right), \quad (7.1)$$

with  $\epsilon_\infty = 0.66$  (0.67),  $\epsilon_{20} = 0.32$  (0.44),  $\sigma = 32$  GeV (23 GeV) for electrons (muons).

The parametrization of the simulated b-tagging efficiency, also shown in figure 2, is  $\epsilon = 0.62$  for  $90 < p_T < 170$  GeV; at higher (lower)  $p_T$  it decreases linearly with a slope of 0.0012 (0.0051)  $\text{GeV}^{-1}$ .

The  $H_T$  and  $E_T^{\text{miss}}$  turn-on curves as a function of the respective generator version shown in figure 3 are parametrized as  $0.5\{\text{erf}[(x - x_{1/2})/\sigma] + 1\}$ . The parameters of the function are summarized in table 2.

For a few of the models of new physics described in section 8, we have compared the acceptance from the full simulation with the result of the simple acceptance model described above. For scenarios with at least two b quarks in the final state, the two calculations typically agree at the  $\approx 15\%$  level or better. However, in scenarios where b quarks are rare or where the lepton isolation is significantly different than in a typical SUSY event, the two calculations may vary by  $\approx 30\%$  or more.

## 8 Models of new physics

We use the search results to constrain several specific models of new physics. Signal samples are generated using PYTHIA with the detector simulation performed using the CMS fast simulation package [39, 40]. For each model considered, we use the simulated signal yields and the background estimations corresponding to the signal region that is expected to give the most stringent limit on the cross section at a given point in model parameter space. Cross section limits are computed using the  $CL_s$  method [35, 36] including systematic uncertainties on lepton efficiency (5% per lepton), luminosity (2.2%), jet energy scale, and b-tagging efficiency. These last two uncertainties are evaluated at each point in parameter space, as they depend on the underlying kinematics of the events. In addition, the simulated event yields are corrected for “signal contamination”, i.e., the oversubtraction of the fake background that would occur in the presence of a real signal. This oversubtraction is caused by same-sign dilepton events with one lepton passing the loose selection but failing the final identification or isolation requirements. The cross section limits are then used to exclude regions of model parameter space.

### 8.1 Models of $pp \rightarrow t\bar{t}$

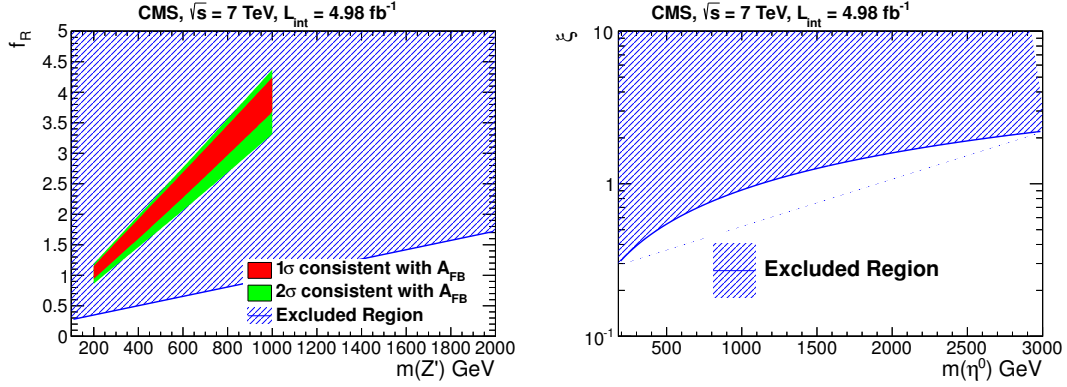
We consider two models that result in same-sign top-quark pairs without significant additional hadronic activity or missing transverse energy. Limits are set based on the results from SR2. The kinematic requirements in this region are modest, and are comparable to those used in the CMS measurements of the  $pp \rightarrow t\bar{t}$  cross section in the opposite-sign dilepton channel [41, 42]. We require only positively charged dileptons, since in the two models considered  $t\bar{t}$  production dominates over  $t\bar{t}$ .

The first model is the  $Z'$  model of ref. [6], which is proposed as a possible explanation of the anomalous forward-backward asymmetry observed at the Tevatron [8–10]. This model introduces a new neutral boson with chiral couplings to u and t quarks. The relevant term in the Lagrangian is  $\mathcal{L} = \frac{1}{2}g_W f_R \bar{u}\gamma^\mu(1+\gamma^5)tZ'_\mu + \text{h.c.}$ , and the model parameters are  $f_R$  and the mass of the  $Z'$ ,  $m(Z')$ . In this model same-sign top pairs are produced predominantly through  $t$ -channel  $Z'$  exchange in  $uu \rightarrow t\bar{t}$ .

The efficiency for  $pp \rightarrow t\bar{t}$  events in the  $Z'$  model is calculated from simulated events, first generated with MADGRAPH and then processed by PYTHIA. We find an efficiency, including branching fractions, of  $0.23 \pm 0.04\%$ , largely independent of  $m(Z')$ . The resulting cross section upper limit is 0.61 pb at the 95% confidence level. This improves the previous CMS limit [17] by a factor of 27. This improvement is due to the factor 140 increase in the integrated luminosity between the two analyses. The limit scales faster than the inverse of the square root of the luminosity since the addition of the b-tag requirement has reduced the background level by a large factor. Our limit is a factor of 2.8 more stringent than that reported by the ATLAS collaboration [43].

In order to compare with other experiments, we also interpret our result in terms of an effective four-fermion Lagrangian for  $uu \rightarrow t\bar{t}$  [44]:

$$\begin{aligned} \mathcal{L} = & \frac{1}{2} \frac{C_{RR}}{\Lambda^2} [\bar{u}_R \gamma^\mu t_R] [\bar{u}_R \gamma_\mu t_R] + \frac{1}{2} \frac{C_{LL}}{\Lambda^2} [\bar{u}_L \gamma^\mu t_L] [\bar{u}_L \gamma_\mu t_L] \\ & - \frac{1}{2} \frac{C_{LR}}{\Lambda^2} [\bar{u}_L \gamma^\mu t_L] [\bar{u}_R \gamma_\mu t_R] - \frac{1}{2} \frac{C'_{LR}}{\Lambda^2} [\bar{u}_{La} \gamma^\mu t_{Lb}] [\bar{u}_{Rb} \gamma_\mu t_{Ra}] + \text{h.c.}, \end{aligned} \quad (8.1)$$



**Figure 4.** Excluded regions in the parameter spaces of the  $Z'$  (left) and MxFV models (right). In the case of the  $Z'$  model we also show the  $m(Z')$  vs.  $f_R$  region consistent with the Tevatron  $t\bar{t}$  forward-backward asymmetry measurements [6].

where  $a$  and  $b$  are color indices. Note that at large  $m(Z')$  the Lagrangian for the  $Z'$  model corresponds to the first term in the effective Lagrangian with  $\frac{g_W^2 f_R^2}{m(Z')^2} = \frac{C_{RR}}{\Lambda^2}$ . In this framework our limit on  $\sigma(t\bar{t})$  results in limits  $\frac{C_{RR}}{\Lambda^2}$  or  $\frac{C_{LL}}{\Lambda^2} < 0.20 \text{ TeV}^{-2}$  and  $\frac{C_{LR}}{\Lambda^2}$  or  $\frac{C'_{LR}}{\Lambda^2} < 0.56 \text{ TeV}^{-2}$ , all at the 95% CL. These bounds are more stringent than those of CDF [45] and ATLAS [43].

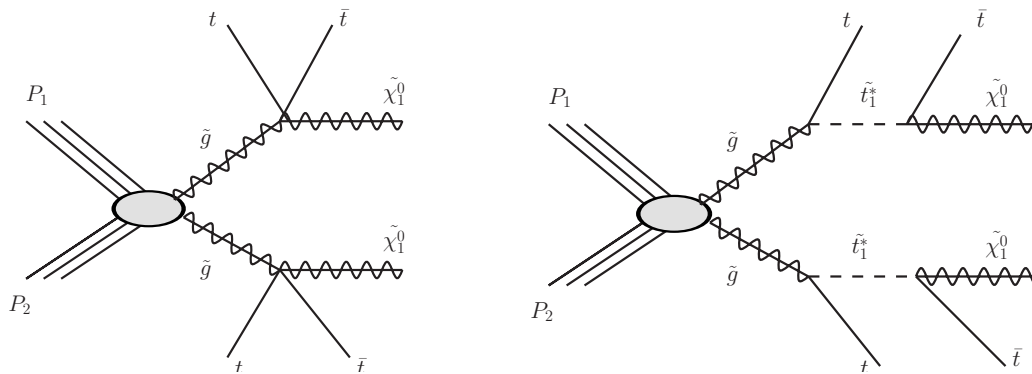
The second model [11–13] has a new scalar SU(2) doublet  $\Phi = (\eta^0, \eta^+)$  that couples the first and third generation quarks ( $q_1, q_3$ ) via a Lagrangian term  $\mathcal{L} = \xi \Phi q_1 q_3$ . Remarkably, this model is largely consistent with constraints from flavour physics. The parameters of this “Maximally Flavour Violating” (MxFV) model are the mass of the  $\eta^0$  boson and the value of the coupling  $\xi$ . In the MxFV model, same-sign top pairs are produced dominantly in  $uu \rightarrow t\bar{t}$  through  $t$ -channel  $\eta^0$  exchange. At small values of  $\xi$  and  $\eta^0$  mass  $u\bar{g} \rightarrow \eta^0 \rightarrow t\bar{t}u$  becomes important. The third production mechanism,  $uu \rightarrow \eta^0 \eta^0$ , is also considered in our analysis. Signal events in the MxFV model are generated using MADGRAPH followed by PYTHIA for showering and hadronization. The decay widths are computed using the BRIDGE program [46].

The limits on the parameter spaces of the  $Z'$  and MxFV models are shown in figure 4. These limits are based on the lowest order cross section calculation. Our bounds disfavor the  $Z'$  model as an explanation of the Tevatron  $t\bar{t}$  forward-backward asymmetry; the MxFV limits are significantly more stringent than those of the CDF experiment [13].

## 8.2 Models with four top quarks and two LSPs from gluino pair production and decay via real or virtual top squarks

In this section we consider two SUSY models of gluino pair production ( $pp \rightarrow \tilde{g}\tilde{g}$ ) with top squarks playing a dominant role in the decay of the gluino. The gluino decays under consideration are (see figure 5):

- Model A1, three-body gluino decay mediated by virtual stop:  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  [47–49];
- Model A2, two-body gluino decay to a top-stop pair:  $\tilde{g} \rightarrow \tilde{t}_1 \bar{t}, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  [4, 50].



**Figure 5.** Diagrams for models A1 (left) and A2 (right).

The assumption of model A1 is that the gluino is lighter than all the squarks, and that the stop is the lightest squark. The dominant gluino decay channel would then be  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ , mediated by virtual top squarks. Model A2 is the same as model A1 but with top squarks light enough to be on-shell. Both models result in  $t\bar{t}t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$  final states, i.e., final states with as many as four isolated high- $p_T$  leptons, four b quarks, several light-quark jets, and significant missing transverse energy from the neutrinos in W decay and the LSPs. For Model A1, the parameters are the gluino mass,  $m(\tilde{g})$ , and the LSP mass,  $m(\tilde{\chi}_1^0)$ . Model A2 has the stop mass,  $m(\tilde{t}_1)$ , as an additional parameter.

These models are particularly interesting because naturalness arguments suggest that the top squark should be relatively light. A possible SUSY scenario consistent with the initial data from the LHC consists of a light stop, with all other squarks having evaded detection due to their very high mass. Furthermore, in order to preserve naturalness, the gluino cannot be too heavy either. Thus, the possibility of a relatively light gluino decaying predominantly into real or virtual top squarks is very attractive; see ref. [4] for a recent discussion.

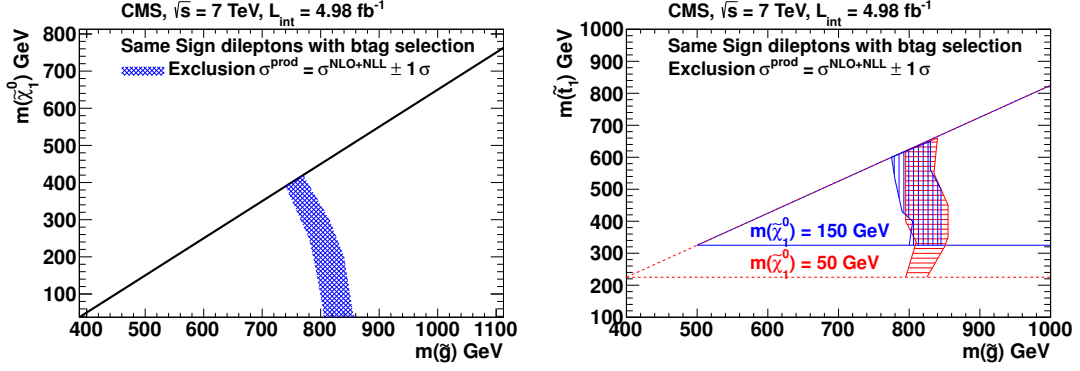
Signal events for models A1 and A2 are generated with PYTHIA. We find that for a large range of parameter space the most sensitive signal region is SR6. This is because these new physics scenarios result in many jets and significant  $E_T^{\text{miss}}$ . Near the kinematic boundaries, where the  $\tilde{\chi}_1^0$  has low momentum, SR4 and SR5 tend to be the most sensitive.

The limits on the parameter space of the A1 and A2 models are displayed in figure 6. These limits are based on the next-to-leading-order (NLO) and next-to-leading-log (NLL) calculations of the gluino pair production cross section [51–53].

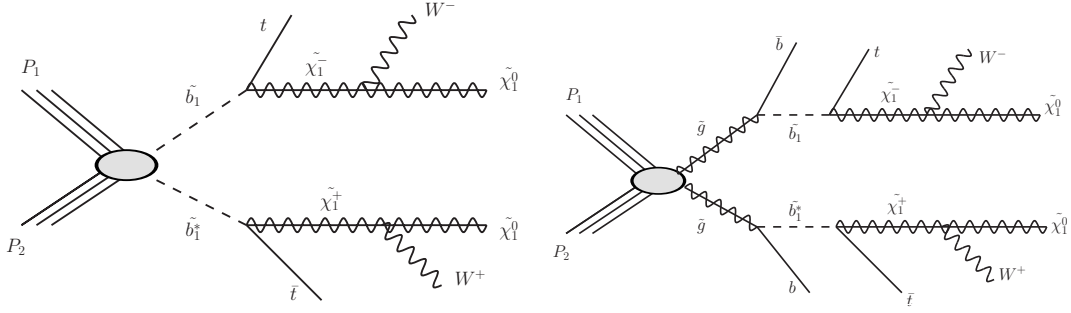
### 8.3 Models with multiple top quarks and W-bosons from decays of bottom squarks

Here we study possible SUSY signals with pairs of bottom squarks decaying as  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$  and  $\tilde{\chi}_1^- \rightarrow W^- \tilde{\chi}_1^0$ . The production mechanisms are (see figure 7):

- Model B1, sbottom pair production:  $pp \rightarrow \tilde{b}_1\tilde{b}_1^*$ ;
- Model B2, sbottom from gluino decay:  $pp \rightarrow \tilde{g}\tilde{g}$  or  $pp \rightarrow \tilde{g}\tilde{b}_1$ , followed by  $\tilde{g} \rightarrow \tilde{b}_1\bar{b}$ .



**Figure 6.** Left plot: exclusion (95 % CL) in the  $m(\tilde{\chi}_1^0) - m(\tilde{g})$  plane for model A1 (gluino decay via virtual top squarks). Right plot: exclusion (95% CL) in the  $m(\tilde{t}_1) - m(\tilde{g})$  plane for model A2 (gluino decay to on-shell top squarks). The lines represent the kinematic boundaries of the models. The regions to the left of the bands, and within the kinematic boundaries, are excluded; the thicknesses of the bands represent the theoretical uncertainties on the gluino pair production cross section from scale and parton distribution functions (pdf) variations. In the case of model A2 we show results for  $m(\tilde{\chi}_1^0) = 50$  GeV (red, with dashed lines for the kinematic boundaries) and  $m(\tilde{\chi}_1^0) = 150$  GeV (blue, with solid line for the kinematic boundary).



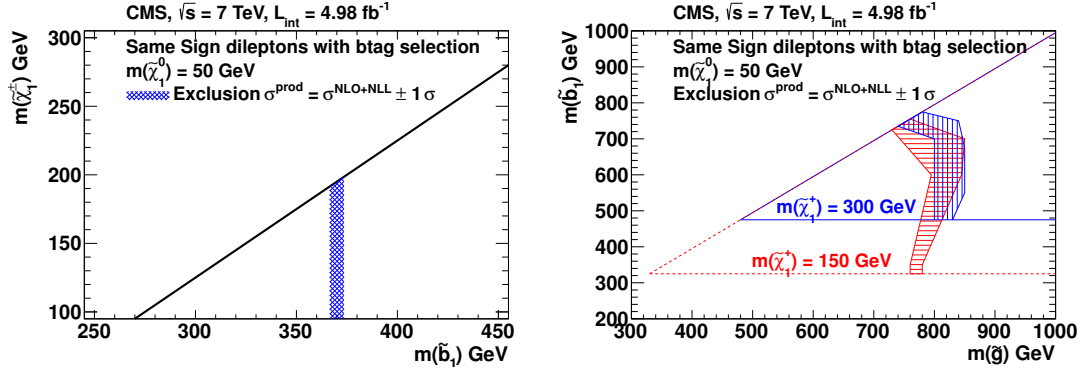
**Figure 7.** Diagrams for models B1 (left) and B2 (right).

In scenarios where the sbottom is the lightest squark, the gluino decay mode of model B2 would have the highest branching fraction.

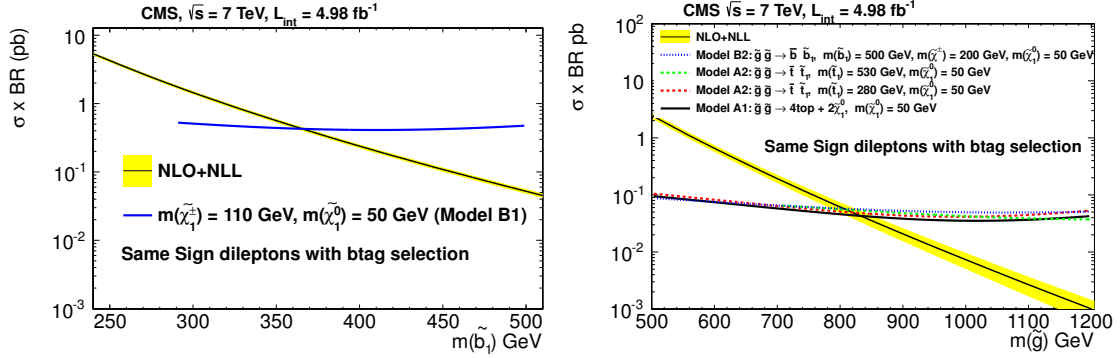
The final states are then  $t\bar{t}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$  for model B1 and, for model B2, a mixture of  $t\bar{t}W^-W^-$ ,  $t\bar{t}W^-W^+$ , and  $t\bar{t}W^+W^+$ , all with two  $\tilde{\chi}_1^0$  and two  $b$  quarks. For simplicity we consider only mass parameters where the chargino and the  $W$  from chargino decay are on shell, except for model B1, where the  $W$  is allowed to be off-shell.

These final states yield up to four isolated high  $p_T$  leptons, and between two and four bottom quarks. For model B1 the parameters are the mass of the sbottom,  $m(\tilde{b}_1)$ , the mass of the chargino,  $m(\tilde{\chi}_1^\pm)$ , and the mass of the LSP,  $m(\tilde{\chi}_1^0)$ . Model B2 has  $m(\tilde{g})$  as an additional parameter.

Signal events for models B1 and B2 were also generated with PYTHIA. The most sensitive signal regions are SR1 and SR4 for model B1, and SR5 and SR6 for model B2. The exclusion regions in parameter space are shown in figure 8 and are based on the NLO+NLL calculations of the production cross sections.



**Figure 8.** Left plot: exclusion (95% CL) in the  $m(\tilde{\chi}_1^0) - m(\tilde{b}_1)$  plane for model B1 (sbottom pair production); Right plot: exclusion (95% CL) in the  $m(\tilde{b}_1) - m(\tilde{g})$  plane for model B2 (sbottom production from gluino decay). The lines represent the kinematic boundaries of the models. The regions to the left of the bands, and within the kinematic boundaries, are excluded; the thicknesses of the bands represent the theoretical uncertainties on the gluino and sbottom pair production cross section from scale and parton distribution functions (pdf) variations. In the case of model B2 we show results for  $m(\tilde{\chi}_1^0) = 150$  GeV (red, with dashed line for the kinematic boundary) and  $m(\tilde{\chi}_1^0) = 300$  GeV (blue, with solid line for the kinematic boundary).



**Figure 9.** Left plot: limits on the sbottom pair production cross section compared with its expected value (NLO+NLL) as a function of sbottom mass in model B1. The cross section limit is insensitive to the choice of LSP mass within the allowed kinematic range. Right plot: limits on the gluino pair production cross section, for models A1, A2, and B2, compared with its expected value (NLO+NLL), as a function of gluino mass.

In figure 9 (left) we show the limits on the sbottom pair-production cross section from model B1 together with expectations for this quantity. The error band on the cross section curve reflects the uncertainty in the choice of scale as well as the associated pdf uncertainties. Within the allowed kinematic range, we exclude  $m(\tilde{b}_1)$  below 370 GeV for model B1. The limits on  $\sigma(\text{pp} \rightarrow \tilde{g}\tilde{g})$  for a few choices of the parameters of A1, A2, and B2 are displayed in figure 9 (right). When compared with the expected gluino pair production cross-section, we find that the gluino mass limit is fairly insensitive to the details of the decay chain, since the limit is driven by the gluino cross section. Models A1, A2, and B2 were also addressed in searches by the ATLAS collaboration [54, 55].



## 9 Conclusions

We have presented results of a search for same-sign dileptons with b jets using the CMS detector at the LHC based on a  $4.98 \text{ fb}^{-1}$  data sample of pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ . No significant deviations from the SM expectations are observed.

The data are used to set 95% CL upper limits on the number of new physics events for a number of plausible signal regions defined in terms of requirements in  $E_{\text{T}}^{\text{miss}}$  and  $H_{\text{T}}$ , the number of b-tagged jets (2 or 3), and also the sign of the leptons (only positive dileptons or both positive and negative dileptons).

We use these results to set a limit  $\sigma(\text{pp} \rightarrow \text{tt}) < 0.61 \text{ pb}$  at 95% CL, and to put bounds on the parameter space of two models of same-sign top pair production. We also set limits on two models of gluino decay into on-shell or off-shell top squarks, a model of sbottom pair production, and a model of sbottom production from gluino decay. In addition, we provide information to interpret our limits in other models of new physics.

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